Varian Ass... Palo Alto CA

IMPROVED FIELD EMITTER CURRENT DENSITIES AND STABILITY THROUGH THE APPLICATION OF A PROPRIETARY PROCESS

CONTRACT MDA972-92-C-0033
QUARTERLY REPORT #1 MAR-MAY '92

I. INTRODUCTION

This brief report details the technical progress made in field emitter development for three different categories. The first category gives the progress for the period between the final proposal (Oct. '91) and the start of this contract (Mar. '92). The second category gives the progress over the three month period (Mar.-May) of this report using internal R&D funds, and third category gives the quarterly progress made using contract funds. As stated in the proposal, progress on Varian's internal development program will be leveraged into this contract, leaving the contract expenditures to be used on tasks unique to the contract goals.

The contract goals are to demonstrate a three-terminal current gain cutoff frequency f_t of at least one GHz at a current density of at least $5A/cm^2$ over a period of 2 hours or more. Varian proposed accomplishing this with a proprietary process using single-crystal materials for both the emitter and the gate. The elimination of grain boundaries are expected to improve problems of stability, tip damage, reproducibility/uniformity and electromigration. At the time of the proposal submission, the efficacy of the single-crystal approach had yet to be demonstrated empirically.

II. PROGRESS PRIOR TO CONTRACT START

Three approaches to a totally single-crystal structure were investigated. They were (1) GaAs thin films, (2) Al-on-GaAs thin films, and (3) high-temperature superconducting $Bi_2Sr_{1.9}Ca_{.9}Cu_2O_8$ thin films. Approach (1) was investigated because of Varian's vast experience with GaAs. GaAs has the advantage of an insulting substrate and the ability to be selectively etched with respect to AlGaAs, neither of which exists for silicon. Both features are needed for the total single-crystal approach. Approach (2) arises from the ease with which single-crystal aluminum is grown on GaAs by MBE. Approach (3) is attractive because these films are available on insulating strontium titrate substrates as a result of another program at the Research Center. The "superconducting" films are single crystal and have a very low resistivity of 300 µΩ-cm at room temperature. They also offer the potential of a very low work function.

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Fabrication problems with approaches (2) and (3) were considerably tougher to solve than with approach (1), and so approach (2) was chosen as the demonstration vehicle for the single-crystal concept. Excellent 1000 A° single-crystal Al films were grown, but a substrate recess etch to raise the breakdown voltage could not be done without dulling the Al tips.

In order to realize approach (1), the low breakdown voltage of semi-insulating substrates had to be raised by the growth of an AlGaAs buffer layer grown by MBE at low temperatures. Breakdown voltages of greater than 200 V were realized. Using E-beam lithography, the structure shown in Fig. 1 was realized. Due to symmetry, the emitter and gate are interchangeable. Up to ~0.8 mA/mm of current could be obtained with this structure in conventional 10^{-6} torr vacuum levels. All previously fabricated non crystalline emitter-gate structures would at most emit 1 nA, if that, before being destroyed by arcing! This represent an improvement of over 10^5 in current and would seemingly validate the single-crystal concept. The 150 μA value exceeds the 20 μA values obtained with non crystallize structures in UHV after extensive bakeouts. These emission values were obtained in the 200-250 V range, above which substrate breakdown appears to be limiting further current increases. Fig. 2 shows a typical I-V characteristic. Electron emission was confirmed by the use of a third electrode.

II. NON-CONTRACT PROGRESS DURING QUARTER

The Varian applications for the field-emitters required that they be scribed into very small die for mounting purposes. The substrate thinning process and scribing resulted in severe degradation of the emission properties. Since this contract will eventually call for the same small die size for microwave measurements, solution of the problem is of double importance.

To thin the substrate, the wafer must be mounted face down in wax. This resulted in quite severe degradation of the device performance no matter how much solvent cleaning was done, with the assorted problems being various combinations of threshold increase, no emission at all, and ease of arc damage. A short etch step was developed to restore the emission characteristics.

A second problem was encountered in scribing the devices. The scribing process invariably broke the tips in the vicinity of the scribe, which would not be a problem except that they shorted the top n^+ GaAs emitter/gate layers to the underlying GaAs substrate, bypassing the insulating AlGaAs layers. A scribe-line etch process was tried without success, necessitating increasing the die size so that the scribe lines run through adjacent devices. Even so, this did not completely eliminate the degradation in breakdown voltage for some unknown reason.

IV. CONTRACT FUNDED PROGRESS DURING QUARTER

Although the contract began the first of March, actual spending did not begin until late April since, as stated in the Introduction, problem areas in common to both Varian and DARPA needs were covered by internal R & D funds.

The achieved current density of ~ 0.8 mA/mm must be improved to at least ~2.4 mA/mm (as stated in the original proposal) to meet the f_t = 1 GHz requirement. If substrate breakdown or MBE defects are responsible for the current limitation, lowering the threshold by a closer emitter-gate spacing and reducing the tip radius should help. If oxide on the surface is responsible for the arcing, a passivation scheme to retard oxidation is needed.

Lowering the threshold by minimizing the emitter-gate gap was investigated. Etching the tips for the minimum time to adequately do the job resulted in little, if any, improvement. A thin AlGaAs layer grown on top the n^+ GaAs tip layer to improve mask adhesion and reduce undercutting was not successful. The reason was because it was necessary to change the GaAs etch (so as to not etch the AlGaAs mask), and the new etch gave the wrong tip profile in the narrow-gap direction. Narrowing the E-beam exposure from 0.35 μm to 0.1 μm was not successful because it was done on the material scheme just described.

Efforts to reduce the tip radius were unsuccessful in reducing the threshold voltage. An additional etch given to the emitter tips without masking (hoping to reduce the tip radius in the manner shown in Fig. 3) did not lower the threshold voltage. Generally, SEM photos of the tip did not seem to indicate a smaller radius, and even when they did, the threshold seemed to remain unchanged. Could it be that the sharper the tip, the thicker the oxide to tunnel through (Fig.4)? Applying voltage to the tip when etching only made matters worse. Ion milling the top side of the emitter did not help.

An HF etch was found to passivate the surface (presumably by terminating the dangling bonds at the surface with fluorine to prevent oxidation) as evidenced by the hydrophobic nature of the surface. The efficacy of this treatment continued to be a matter of study at the close of this reporting period.

V CONTRACT SUMMARY

Contract charges began April 20, '92. The approach remains unchanged from the proposal, with only a factor of ~3 improvement in the current density needed to complete Task 1 in the SOW (Appendix). So far there are no areas of concern.

Plans for the next quarter are to achieve the current density improvement using the same materials structure, and begin the mask design for the microwave device studies.

R&D STATUS REPORT
PROGRAM FINANCIAL STATUS

VORK BREAKDOWN	CUMULATIVE TO DATE			AT COMPLETION		
TRUCTURE OR ASK ELEMENT	PLANNED EXPEND	ACTUAL EXPEND	% COMPL	BAC*	LRE*	REMARKS
ubtotal	$13,600	$18,031	16%	112,592	112,592	
lanagement Reserve				0	0	
nallocated Resources				0	0	
OTAL	$13,600	$18,031	16%	$112,592	$112,592	

Budget At Completion (BAC) changes only with the amount of any scope changes (not affected by underrun/overrun)
* Latest Revised Estimate (LRE)

Statement A per telecon Dr. Hui
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JK 10-5-92

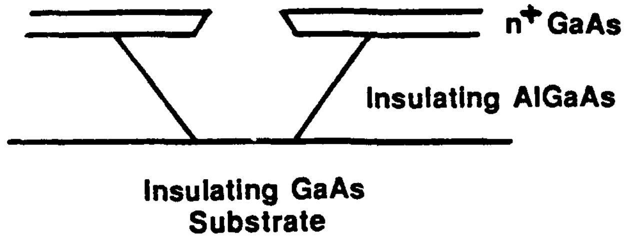

Fig. 1 GaAs emitter-gate/anode structure

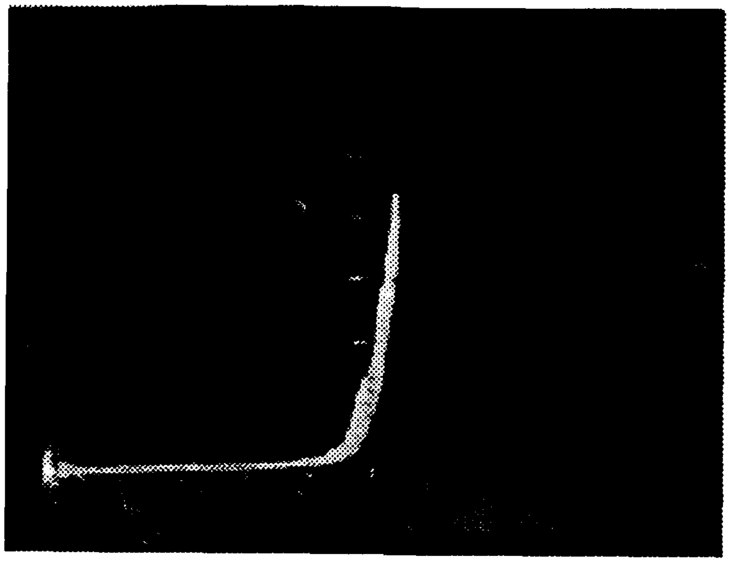

Fig. 2 Emission I-V Characteristic (50V, 10 μA/div)

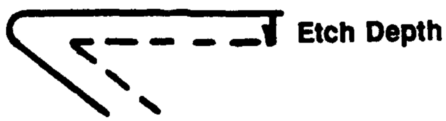

Fig. 3 Tip sharpening by unmasked etching

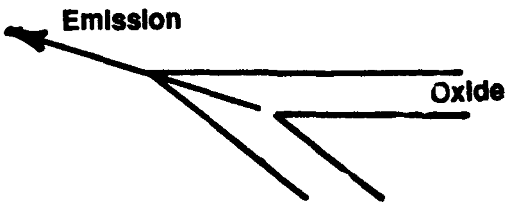

Fig. 4 The sharper the tip, the thicker the oxide